MICROCLIMATE-CONTROLLED (THERMALIBRIUM) CLOTHING SYSTEMS FOR MILITARY APPLICATIONS

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1. INTRODUCTION

Progress in weapons development has emphasized the need for multifunctional clothing to protect the individual exposed to extreme climates and/or toxic environments. This need is particularly acute when individuals are engaged in disposing toxic munitions or operating military equipment such as armored vehicles, helicopters or low-speed aircraft in hot and hot-humid environments. To meet these needs, the U.S. Army has designed and developed microclimate-controlled clothing. The basic difference between this type of clothing and conventional protective ensembles is the technique used to control the flow of heat and sweat from the skin surface to the outside environment. In microclimate-controlled clothing such control is accomplished by closed-loop circulation of heated or cooled fluids close to the skin surface or by circulation of heated ambient or conditioned air inside the clothing. In conventional clothing such control is attempted by varying the number and type of clothing layers worn at one time.

To function best the human body should not be restricted in locomotion and other physical activities; should be protected against excessive heat, cold and other disabling environments; and should be maintained in thermal balance. Clothing, no matter of what type, is not fully adequate in any of these respects. The inadequacies can become critical in the case of military clothing. Protection against toxic environments can usually be realized by employing fabrics and treatments specifically developed to defeat such toxic agents. A high degree of clothing adjustability can be achieved by novel pattern designs. However, to maintain the clothed individual in thermal balance the heat and sweat produced by the body must be transported to the outside environment at the same rate the individual produces it. In other words military clothing, to function best, must be dynamically responsive to body needs. This is no simple task. No pro-

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tective clothing available in military supply channels presently meets this criterion.

2. DESIGN PRINCIPLES

The building blocks conceptually needed for microclimate-controlled protective clothing systems are shown in Fig. 1. Principal components of microclimate-controlled clothing are:

1. The basic ensemble which provides all the protective capabilities necessary for the specific mission.
2. A microclimate distribution garment tailored for the specific activity.
3. A powered microclimate regulation device to control the temperature, humidity and flow rate of the ventilating air or circulating fluid moving through the distribution garment.

Environmental protection is realized through the insulative properties of the basic ensemble and is augmented by the energy transported by the conditioned air or fluid moving through the microclimate distribution garment. Protection against toxic agents and thermal radiation from nuclear and flame weapons is accomplished by extensive use of clothing materials and treatments developed specifically to meet such military requirements. Stretch-type materials and bias-cut fabrics are used extensively to achieve a high degree of clothing adjustability. Use of such materials and cutting techniques bridge over several problems which, to date, have precluded the engineering of close-fitting clothing that impose little or no restriction on body movement.

Microclimate distribution garment. The microclimate distribution garment is either a spaced ventilated undergarment through which conditioned or ambient air flows and is distributed over the body surface, or it is a knitted undergarment through which a closed loop network of flexible "Tygon" vinyl plastic tubing is interwoven to provide a closed path for the liquid circulating through the garment. Selection of either type (gaseous or liquid) as well as its specific design and surface coverage, i.e., total body or torso, is dependent on the specific protection needed and the environment in which such protection must be given.

Figures 2 and 3 show a typical total body and torso air distribution garment, respectively. Figure 4 shows a typical water-cooled undergarment and a water-cooled vest. For example, cooling of tank crewmen operating in hot and/or hot-humid areas can be easily achieved by ventilating the torso area with conditioned air or by circulation of cool water through a water-cooled vest. However, when these vehicles are operating in a toxic environment all ventilating air for microclimate control must be filtered prior to its use in the clothing. Consequently, under these conditions, a closed-loop, water-cooled system for tank crewmen would be preferred.

Powered microclimate regulation devices. To control the temperature, humidity and flow rate of the ventilating air or the temperature and flow rate of the circulating water, powered heat regulation devices must be available. These may be battery-powered, self-powered or remotely powered from the vehicle in which the individual is performing his mission. The low power density of rechargeable batteries limits their use to clothing systems that are required to protect the individual for periods of 2 to 3 hours. However, the technology in semiconductor materials is such that it is possible to engineer self-powered heat regulation devices for protective clothing. Figure 5 shows a thermoelectric powered heating-ventilating system capable of delivering continuously 18 cfm of heated or ambient air at a static pressure of four inches of water. This unit fully fueled for 8 hours of continuous operation weighs 11.9 lbs. The operation of this unit is shown in Fig. 6.

3. PROTECTIVE CLOTHING SYSTEM FOR EXPLOSIVE ORDNANCE DISPOSAL

This system (Fig. 7) consists of a one-piece butyl-coated ensemble; a spaced microclimate distribution garment worn directly under the coated butyl layer; insulated butyl boots; butyl handwear; a shoulder suspended helmet; a lightweight communication headset; and a battery-powered ventilating backpack for microclimate control and life support. All components are shown in Fig. 8. The design and surface coverage of the microclimate distribution garment selected for this system is critical and was specifically tailored to perform several functions. The distribution garment chosen is a five-layer-spaced system through which the ventilating air in contact with the skin surface is forced to move to the extremities,then reverse its path and move countercurrently through a spaced layer parallel to but separated from the ventilating layer before the air is discharged to the outside environment.

The flow path of the ventilating air through the fabric system is shown in Fig. 9. Partitioning of the ventilating stream from the exhaust stream assures high turbulence over the skin surface. This effectively increases the overall heat and mass transfer coefficients prevailing on the skin surface. This also increases the cooling capability of the total system. The partitioned exhaust air serves as a buffer layer between the outside environment and the ventlating air in contact with the skin surface. Such a buffer layer increases the insulative characteristics of the total clothing by shielding the ventilating air stream against heat leakage into the clothing when exposed to solar radiation; it augments the protective capabilities of the system by purging any in-board leakage of toxic agents that could penetrate the outer butyl-coated fabric garment through punctures or tears. The redundant butyl-coated fabric layer used to separate the ventilating and exhaust air streams serves as a secondary barrier to potential penetration of toxic agents.

All materials used in the fabrication of this ensemble are either stretchable or cut on the bias to achieve a high degree of mobility. The ensemble is relatively form-fitting and highly flexible. Butyl insulated boots and butyl gloves are used to protect the extremities. Connection of the handwear and footwear to the suit is achieved by locking plastic disconnects. A gas-sealing zipper is used for the main closure of the suit. All hardware connectors and closures are shielded by butyl rubber protectors.

Helmet. The helmet consists of a rigid polycarbonate shell with a large clear area to provide nearly unrestricted visibility. It is supported on the shoulders and its position is adjustable on either side for better fit. Ventilating air for breathing and cooling is delivered to the head area through a built-in manifold in the air distribution garment. At the base of the visor there is an oral-nasal deflector to direct exhaled gases away from the visor. This prevents fogging on the visor and CO_2 buildup in the helmet. The deflector is currently being redesigned to permit direct breathing from various types of emergency-breathing, life-support devices.

Life Support System for EOD. The connecting link between the suited man and the outside environment is the life-support backpack. This consists of three basic components: (1) a high efficiency blower; (2) an expendable filter; and (3) a power pack to drive the blower. The expendable filter and blower are located in a molded plastic housing carried on the upper section of the man's back. The power pack consists of two waist-belt-suspended pouches containing rechargeable Ni-Cd batteries. The power pack is readily accessible for fast replacement in contaminated environments.

Disposable Filter. The disposable filter whose capacity is approximately four times that required for a normal EOD mission was specifically designed to clean all ventilating air entering the suit to the same degree now provided by the M-17 Field Protective Mask. Figure 10 shows the filter canister and its location when nested in the backpack. While it has been established that nearly all Army EOD missions can be handled by using the filtered-air life-support backpack, the protective ensemble is designed to be easily interphased to a self-contained air supply system when CB agents contamination is anticipated to be exceedingly high.

4. AIR-CONDITIONED CLOTHING FOR ARMY AIRCREWMEN

The Army's extensive use of helicopters and other aircraft to provide logistical and tactical support to ground troops in Southeast Asia brought into focus the need for an air-conditioned clothing system to relieve the physiological stress imposed by hot-humid environments on the individual flying such aircraft. Generally, the only type of environmental control provided in current Army aircraft is ventilation of the cabin area by ram air entering through air scoops while the aircraft is in flight. Although this method of purging the cabin when flying is of definite value, frequently such cabin ventilation with ambient air has been found inadequate because of the low altitude. The problem becomes much more severe when such aircraft are required to remain on the flight line for prolonged periods prior to actual take-off. During these pre-flight delays the temperature and humidity in the cabin area become very stressful. Many flights may have been aborted following such pre-flight delays because pilots could not continue in the stressful environments prevailing inside the aircraft.

Spaced Garments. To alleviate these conditions the U.S. Army Natick Laboratories engineered a spaced garment to be worn directly over the underwear and under the standard high temperature resistant "Nomex" flight clothing and associated equipment, i.e., the aircrew armor, the life jacket, and the harness used in such aircraft as the Mohawk to secure the pilot and navigator to the ejection seats. Development of the air conditioning equipment to condition aircrewmen's clothing is the responsibility of another agency and will not be discussed here. However, studies conducted at Natick provide the information necessary for such development.

Air Distribution System. The air distribution system, shown in Fig. 11, consists of a layer of spacer fabric sandwiched between two layers of Lycra fabric. This material was selected to provide adequate spacing for air circulation between the two Lycra fabrics while maintaining a low air flow resistance. Air manifolds located between the two Lycra fabrics and near the lumbar region assure air circulation to the chest and back section of the torso.

Conditioned air enters the distribution garment through two quick-disconnect fittings, one connected to the left air manifold and the other connected to the right air manifold. The garment configuration resembles an abbreviated, one-piece underwear. As shown ir Fig. 11, the garment can be put on or taken off simply by opening or closing the "Velcro" front closure running from the neck (jugular notch) over the thorax, the abdomen to the iliac region, and then to both thighs. The air distribution system has exceptional adjustability; consequently, it imposes little or no restriction of body movement on the individual wearing it. This adjustability is achieved by bias cutting of the spacer fabric and by adding stretchable panels in those areas where body movement requires extensive dimensional change of the garment. Since all fabrics used are air permeable, flow of both sensible and insensible perspiration leaving the body surface is not impeded. Circulation of the conditioned air over the skin surface for body cooling is assured by the low air permeability of the flight suit, the aircrewman armor and other personal equipment worn over the air distribution garment. Figure 12 shows three soldier volunteers wearing the air-conditioned clothing and fully dressed for combat mission.

5. PERFORMANCE OF THE EOD CLOTHING

The physiological adequacy of this clothing system was checked by soldier volunteers performing work equivalent to EOD activities while exposed to the following chamber environments: (1) 105°F and 20% RH; (2) 95°F and 50% RH; (3) 85°F and 96% RH; and (4) 85°F and 75% RH. These studies were conducted by the U. S. Army Research Institute of Environmental Medicine at Natick. Figure 13 shows the physiological response of one of the test subjects as reflected by the rectal temperature T_r, body temperature T_b, and the mean-weighted skin temperature T_s as a function of exposure time. The sharp decrease followed by the sharp rise in T_b and T_s during the first hour of the study reflects the high evaporative-cooling capability of the system when the skin surface is saturated with sweat. Then, as the skin surface dries, the cooling rate decreases to that required to keep the body thermally neutral. This effect is reflected by the relatively constant T_r, T_b, and T_s prevailing during the last hour of the test.

To confirm the system's protective capability when an individual is exposed to toxic agents, tests were conducted by the Medical Research Laboratory at Edgewood Arsenal. Three soldier volunteers dressed in the EOD Clothing were exposed inside a chamber laden with chloropicrin gas. The concentration of chloropicrin in the chamber was set at 1000 mg/m^3. This concentration is estimated to be approximately ten times higher than any condition expected in a field mission. The chamber temperature and humidity during the tests were maintained between 108 and 110°F and approximately 20% RH. Each of the three volunteers was exposed twice. Each study lasted two hours. During the first hour each individual was required to walk around the chamber, and during the second hour he was required to perform light exercise. Heart rate and rectal temperature were monitored continuously. At no time during the six 2-hour exposures did the rectal temperature exceed 102°F nor the heart rate reach 180 beats per minute. At the end of each test the subject, while still in the chamber, was asked to disconnect the air hoses at the suit inlet fittings to simulate exchange of a spent backpack for a fresh one. No leaks of chloropicrin gas were detected by the subjects at any time during the studies. At the completion of each test all three subjects stated that under the conditions of test they were reasonably comfortable. Under the same conditions, an individual wearing the standard M-3 Toxicological Protective Suit shown in Fig. 14 would have collapsed from heat stress in less than thirty minutes.

6. PERFORMANCE OF THE AIR-CONDITIONED CLOTHING FOR ARMY AIRCREWMEN

The effectiveness of this clothing system was checked by soldier volunteers exposed to environments simulating those in a typical aircraft waiting to take off in a hot-humid area. The objective of these studies was to demonstrate the degree of physiological stress imposed under such conditions and determine to what degree such stress can be reduced by the use of air-conditioned clothing.

After selecting the proper size clothing system, each test subject was weighed nude, and then weighed again when fully dressed. Following the weighing, each subject entered the climatic chamber and sat at rest, simulating his pre-flight period in the aircraft. Figure 15 shows test subjects in the chamber. Temperature and humidity in the chamber were set at 125°F and 25% RH. This high-temperature and low-humidity condition was used to simulate the "greenhouse" effect of solar heat passing through the plastic canopy of an aircraft. This effect produces a high radiant heat condition within the aircraft cabin. It should be noted that the total enthalpy of the environment at 125°F and 25% RH (48.9 Btu/lb) reflects the exact enthalpy of the hot-humid environment prevailing outside an aircraft under ambient conditions of 95°F with an 83% relative humidity. Each test subject was continuously monitored while in the chamber to record his physiological responses to the stressful environment. Specific physiological measurements taken included: (a) Rectal temperature (T_r); (b) Mean weighted skin temperature (T_s); (c) Heart rate; (d) Metabolic heat production (M); and (e) Sweat production. Mean body temperature (T_b) was calculated as the weighted average of $1/3T_s + 2/3T_r$.

Each subject was tested wearing both the standard flight clothing and the air-conditioned aircrewman clothing system with half the men wearing each item each day to assure that any significant differences obtained were attributable to using the conditioned aircrewmen's clothing and not to differences between individuals or to acclimatization. Consequently, the physiological response of each test subject when wearing air-conditioned aircrewmen clothing could be compared directly with the response of the same individual when wearing standard flight clothing.

Results from these studies suggest that personnel wearing the standard flight clothing and equipment used when flying military aircraft in hot and hot-humid areas are under a severe heat stress if, fully dressed for combat missions, they are required to sit in the aircraft on the flight line for extended periods prior to being cleared for take-off. This is reflected by the rise in body temperature, sweat production and heart rate. Figures 16 and 17 show two typical cases of heat exhaustion following these exposures to the simulated air craft cabin environment (125°F and 25% RH) used for these studies. Figure 18 shows the mean rise in rectal temperature of the same individual when using the air-conditioned clothing and when using the standard flight clothing and equipment now required for combat missions in Southeast Asia. It is apparent that when wearing the air-conditioned clothing the individual was essentially in thermal balance. Figure 19 shows the change in body temperature as a function of time. It also shows that the body temperature of individuals wearing the standard flight clothing rose approximately 2°F per hour, while men wearing the air-conditioned clothing show little change or no change.

Sweat production rates obtained in these studies also show significant differences. Figure 20 shows that the sweat production of individuals dressed in standard clothing is approximately 2.3 times higher than that when wearing the air-conditioned clothing. The sweat evaporation rate when using the air-conditioned clothing was found to be 1.7 times greater than that realized when wearing the standard flight clothing. It can be predicted from these data that extended exposure of crewmen wearing standard flight clothing to these hot conditions would lead to physiological exhaustion. However, when using air-conditioned clothing they could be exposed indefinitely without imposition of any significant stress.

7. CONCLUSIONS

Clothing, regardless of type, restricts normal body motion and obstructs the transport of heat and sweat from the skin surface to the outside environment. This is particularly true of military clothing which must provide protection against a multitude of natural environments and man-imposed toxic hazards. No protective clothing available in military supply channels remotely approaches the dynamic responsiveness the body requires of clothing.

Studies by U. S. Army Natick Laboratories show conclusively that close control of the microclimate inside clothing can bridge over many technical problems which now preclude the engineering of multifunctional clothing systems for military applications.

Although the technical feasibility of microclimate-controlled clothing for general field use is still a long-range goal of the Army, the use of such systems for special applications is now a reality. Besides the two systems discussed in this paper several other functional systems based on the same design principles have been delivered and are now in actual use, or are scheduled for field testing by the U. S. Army. Typical of these are the protective clothing system delivered to NASA Manned Spacecraft Center, Houston, Texas for use by rescue personnel entering the space vacuum chamber; the environmental protective ensemble delivered to NASA Marshall Space Flight Center at Huntsville, Alabama, to be used in checking the Saturn V booster; the microclimate-controlled clothing for tankcrewmen, and the Protective clothing used by laboratory personnel at Ft. Detrick.

It can be concluded that substantial progress has been made toward the development of scientific, fully effective, protective clothing, capable of sustaining soldiers in the most adverse environments.

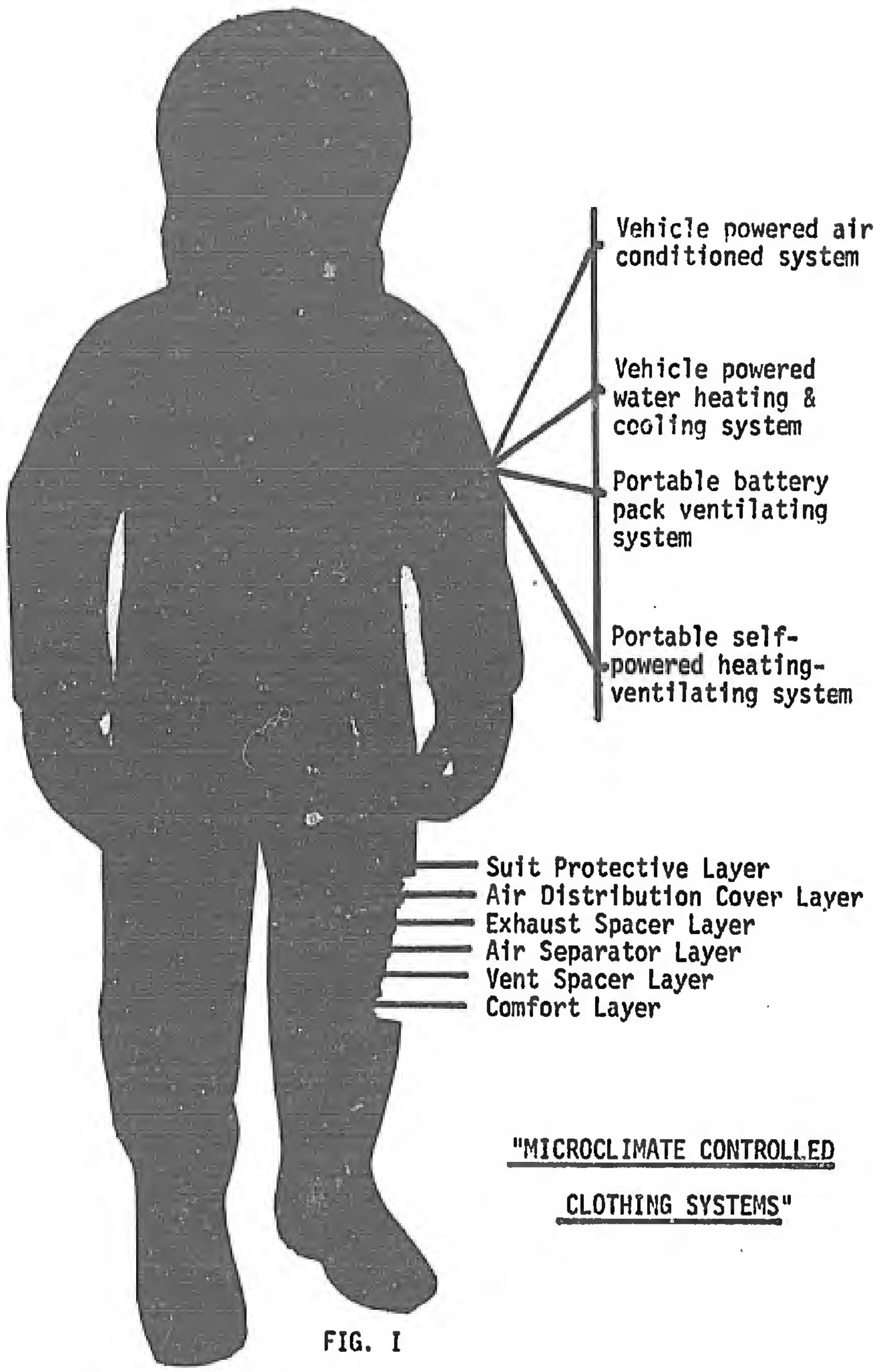
Vehicle powered air conditioned system
Vehicle powered water heating & cooling system
Portable battery pack ventilating system
Portable self-powered heating-ventilating system
Suit Protective Layer
Air Distribution Cover Layer
Exhaust Spacer Layer
Air Separator Layer
Vent Spacer Layer
Comfort Layer
"MICROCLIMATE CONTROLLED CLOTHING SYSTEMS"

FIG. I

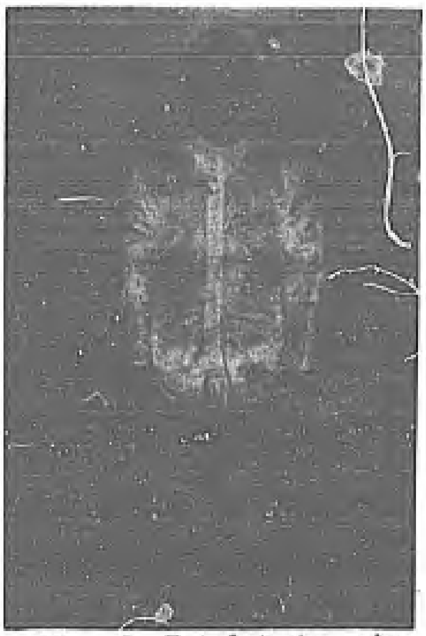

Fig. 2. Total body, air distribution garment

Fig. 3. Torso, air distribution garment

Fig. 4. Water-cooled vest and undergarment

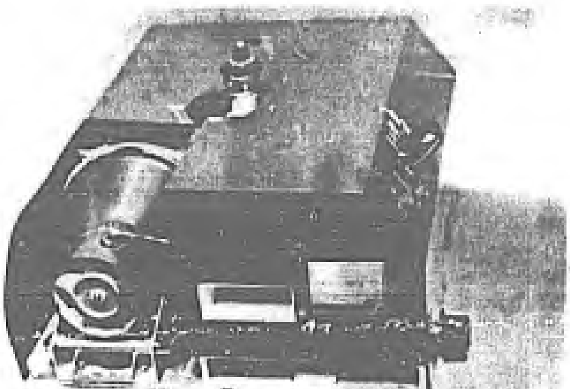

Fig. 5. Thermoelectric unit

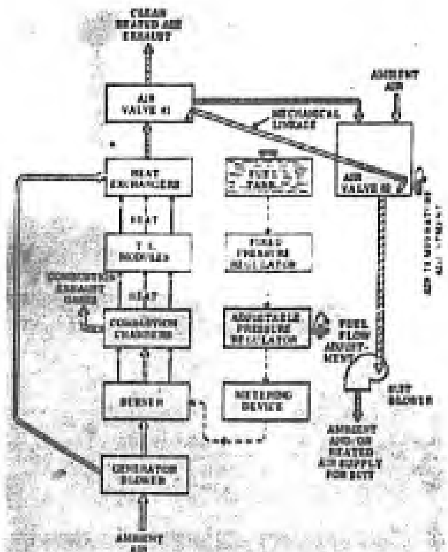

Fig. 6. Flow diagram of thermoelectric unit

Fig. 7. EOD man working

Fig. 8. EOD ensemble components

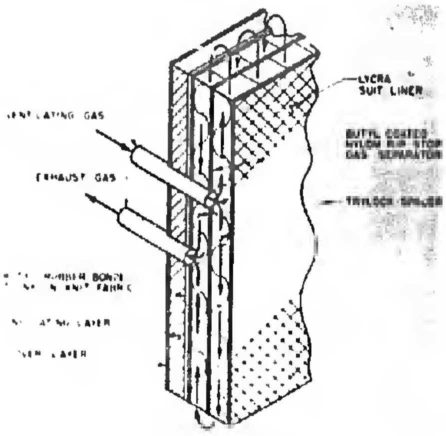

Fig. 9. Flow path through fabric system

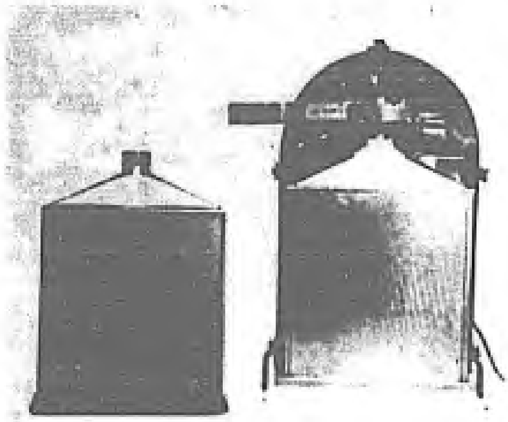

Fig. 10. Filter and its location in the pack

Fig. 11. Air distribution garment

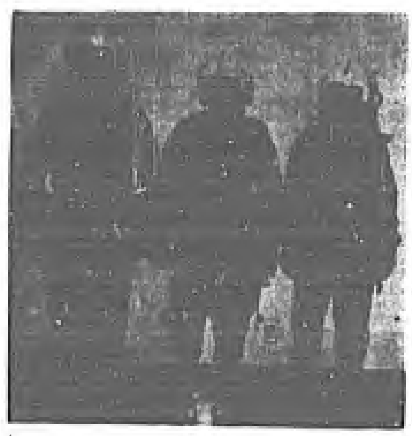

Fig. 12. Aircrewmen wearing air-conditioned clothing

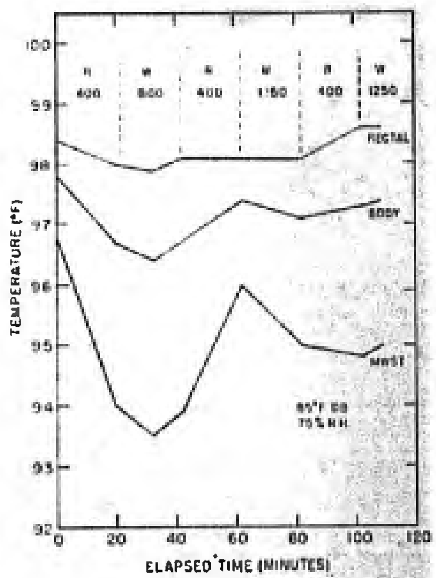

Fig. 13. Physiological responses during test

Fig. 14. M-3 toxicological protective suit and its components

Fig. 15. Test subjects in chamber

Fig. 16. Heat casualty

Fig. 17. Heat casualty

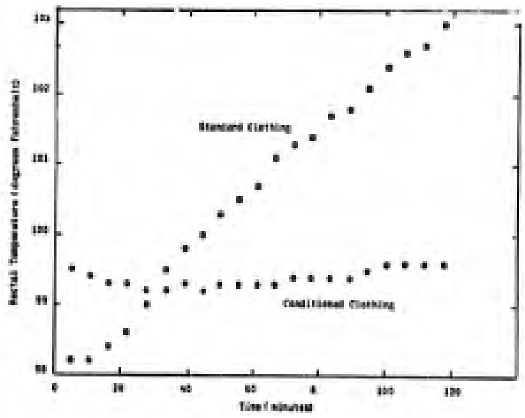

Fig. 18. Rectal temperature as a function of time

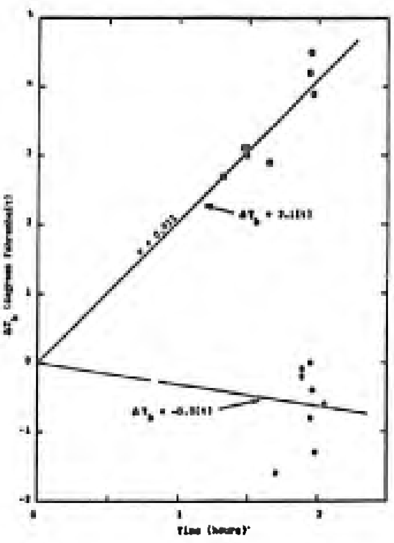

Fig. 19. Body temperature as a function of time

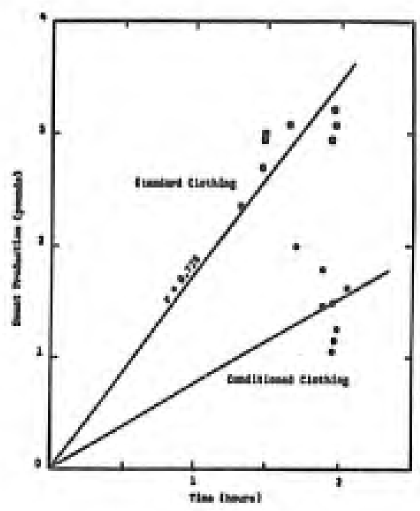

Fig. 20. Sweat production as a function of time.